NASA'S TELECOMMUNICATIONS STRATEGY FOR MARS EXPLORATION

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Abstract

Over the past year NASA and its international partners have carried out a significant planning activity to re-assess the sequence for Mars exploration over the coming decade. The resulting new program of Mars exploration poses a wide range of telecommunications challenges. We describe here strategies to meet these challenges. The need for increased data return will be quantified in terms of specific science goals and science instrument capabilities, while operational paradigms for second-generation lander/rover surface activities will drive link connectivity requirements. Robust characterization of entry, descent, and landing system performance will demand a combination of low-threshold, low-rate "semaphore" signaling to Earth along with high-rate proximity link telemetry collected from relay assets positioned above the descent vehicle. The potential role of competed, low-cost, scout-class missions in the new program architecture, and their mission-enabling dependence on energy-efficient relay communications, will be described. A low-cost approach to meeting these needs is centered around the development of a standardized proximity link communications/navigation payload that can be flown on all future Mars science orbiters and, in the longer term, on dedicated Mars telecommunications orbiters. The evolving capabilities of the orbiting Mars infrastructure as envisioned in the new program architecture will be quantified, demonstrating the potential for orders-of-magnitude increase in data return from the Martian surface by the end of the decade.

1 Introduction

Over the coming decade, an international fleet of spacecraft will carry out the most intensive exploration to date of another world in our solar system. A wide range of landers, rovers, and aerobots will conduct detailed *in situ* investigations, culminating in an eventual return of Martian surface, subsurface, and atmospheric samples to Earth for detailed laboratory evaluation. The success of this program of exploration will demand the implementation of an orbital infrastructure to support the telecommunications and navigation needs of this mission set.

In Section 2, we present an overview of the currently envisioned program over the next decade, highlighting some of the specific telecommunications and navigation challenges of each mission. Section 3 addresses strategies for meeting the telecommunications needs of the aggregate mission set, while Section 4 describes desired characteristics of a proposed next-generation standardized proximity link comm/nav payload. Section 5 summarizes the recommended strategy and identifies areas for future work.

2 Program Overview

Over the past year, a comprehensive replanning activity involving NASA and its international partners has been carried out, establishing a new program of Mars exploration for the coming decade. The new plan incorporates program recommendations made after the loss of the Mars Climate Orbiter and Mars Polar Lander, and integrates a systematic science strategy laid out by the Mars Exploration Payload Advisory Group.

A timeline of the planned mission set is illustrated in Figure 1. Key elements of the program include:

- *Sample Return:* A driving element of the program is a planned Mars Sample Return (MSR) mission launched in the 2011 Mars launch opportunity. This mission would utilize a NASA lander and a CNES orbiter, working together to accomplish sample return. The NASA lander, in its current baseline configuration, would gather a scientifically-selected set of surface, sub-surface, and atmospheric samples and launch them into Mars orbit aboard a Mars Ascent Vehicle (MAV), carrying the samples in an Orbiting Sample Canister (OSC). The CNES orbiter would retrieve the OSC and return it to Earth for sample analysis.
- *Technology precursor missions:* The Mars Sample Return mission requires a number of key enabling technologies. For the MSR lander, second-generation entry/descent/landing (EDL) technologies will enable safe, precision landing to an accuracy of 6 km or better through a combination of high-accuracy pre-entry approach navigation, guided post-entry aeromaneuvering, and active hazard detection and hazard avoidance during terminal descent. For the MSR orbiter, critical technologies include aerocapture, on-orbit rendezvous, and sample handling. The 2007 NASA "Smart Lander" and the 2007 CNES Orbiter missions will validate all of these key technologies prior to their use in the actual 2011 sample return. This notion of "feed-forward" technology demonstration is a important aspect of the new architecture.
- *Orbital reconnaissance:* To support site selection for sample return, in terms of both scientific and site safety considerations, the program includes a strong suite of remote sensing orbiters, including Mars Global Surveyor (NASA, '96), Mars Odyssey (MRO) (NASA, '01), Mars Express (ESA, '03), Nozomi (ISAS, '98), Mars Reconnaissance Orbiter (NASA, '05), CNES Orbiter ('07), ASI/NASA Science Orbiter ('09).
- *Competed scout-class missions:* In addition to the sample return mission and feed-forward technology precursor missions, the NASA program also incorporates competed scout-class missions, starting in the 2007 opportunity. These cost-capped, PI-managed missions are intended to broaden the science scope of the program and encourage innovative mission concepts that quickly respond to new scientific discoveries.
- *Telecommunication relay capabilities:* Recognizing the importance of telecommunications and radio-based navigation to the aggregate set of Mars missions, the program also provides proximity link relay telecommunications and navigation services based on an evolving orbital infrastructure. Near-term science orbiters such as MGS, Odyssey, MRO, and CNES'07 will carry proximity link telecommunications payloads. In addition, the program includes the first dedicated Mars telecommunications spacecraft, the 2007 ASI/NASA Marconi telecommunications orbiter.

A number of elements in the program will require proximity link telecommunications and navigation services. In 2003, the NASA Mars Exploration Rover (MER) mission will land two rovers on the surface to carry out robotic field geological investigations. These rovers, with nominal surface lifetimes of 3 months each, will utilize both X-band Direct-To-Earth (DTE) communications and UHF relay communications to carry out their mission. The X-band link, with a 15W SSPA and 26 dBi directional antenna, is based on Mars Pathfinder heritage and will support commands, engineering and floor science telemetry return. The UHF proximity link, with a 10 W transmitter and low-gain monopole antenna, will provide enhanced science telemetry return, with a target of at least 50 Mb/sol average through the Mars Odyssey orbiter. The MER mission also requires collection of real-time telemetry during EDL to support feed-forward fault diagnosis in the event of an anomaly.

In this same opportunity, Mars Express will deploy the ESA Beagle-2 lander. This small, scout-class lander will have not DTE link, instead relying solely on UHF relay communications through Mars Express, and potentially through Mars Odyssey, for its command and telemetry needs. Data return will average 15 Mb/sol using a 5 W UHF transceiver. The surface lifetime goal for Beagle-2 is 6 months.

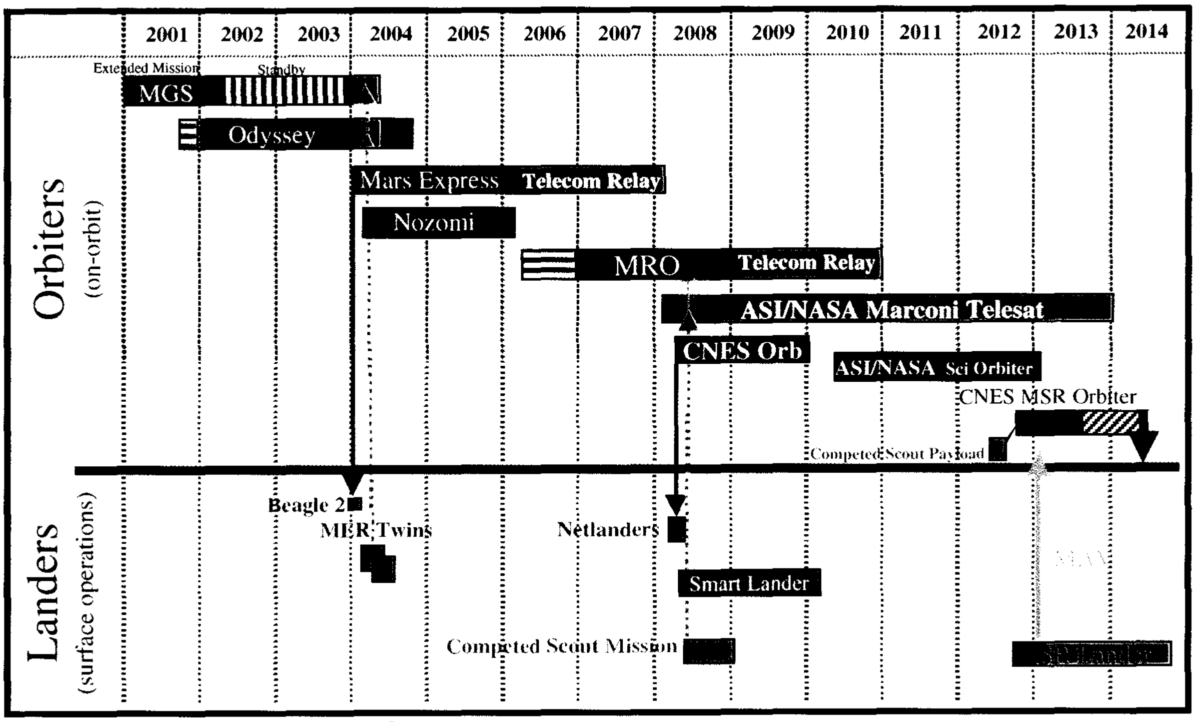

Figure 1: Mars exploration timeline

In 2007, the NASA smart lander mission will again utilize a combination of DTE and relay communications to carry out its mission. Give the technology feed-forward role of this mission in validating new 2nd-generation EDL technologies, high-rate real-time EDL telemetry will be essential. Once on the surface, the larger landed mass of this lander, relative to the 2003 MER landers, will allow a somewhat more capable DTE link. Once again, however, relay communications are expected to be used to significantly augment the data return possible over the DTE link.

In this same opportunity, the CNES '07 orbiter will deploy four small, scout-class Netlanders to the Martian surface. With a design lifetime of one Martian year, these landers will utilize relay communications via a 6.5-W UHF transponder, supporting routine daily data return of 3 Mb/sol/lander, plus 70 Mb/week/lander of science telemetry. In addition, the Netlanders will carry the NEtlander Ionosphere and Geodesy Experiment (NEIGE) [Barriot, et al., 2000] which will add a second, higher-frequency lander-to-orbiter link frequency, coherent with the UHF return link frequency, in order to measure and separate the effects of ionospheric and geodetic effects on the observed link Doppler shifts.

Competed NASA scout-class missions in the 2007 and 2011 opportunities will likely utilize relay communications in carrying out their mission. Because these missions will be selected through a competitive AO process, we do not yet know the detailed proximity link requirements of these missions. However, previous scout-class mission studies have included such concepts as globally distributed microlanders or penetrators, short-duration (<30 min) powered or unpowered aircraft, long-duration (one week or more) aerobots/balloons, and reflight of an MER-class rover.

Finally, the 2011 sample return mission presents a number of telecommunications challenges. Once again, real-time EDL communications will be required for an asset of this cost and programmatic importance. With a relatively large landed mass, this mission will utilize both DTE and relay communications. Data volume and contact time requirements have not yet been derived, but it is expected that the operational complexity of surface sample collection activities will drive the need for frequent, high-bandwidth communications. The launch of the Mars Ascent Vehicle (MAV), representing the first launch of a

Users	Launch Date	Key Characteristics	Key Requirements
MER-A/B (NASA)	2003	• Latitude: -15 to +10 deg • Surface ops: 3 mos • DTE: X-band, 15 W RF, 26 dB HGA) • Proximity: UHF, 10 W RF transponder, monopole antenna • Power: Solar/battery	• Approach nav: 0.75 deg FPA error @ E-1d, 3σ • Surface pos: <30 m in 3 sols • EDL Comm (DTE and/or prox link) • Data volume: 50 Mb/sol avg • Contact Freq: AM & PM
Beagle 2 (ESA)	2003	• Latitude: 0 to 10 deg • Surface ops: 6 mos • DTE: None • Proximity: UHF, 5 W RF transceiver • Power: Solar/battery	• Approach nav: 2.5 deg FPA error @ E-10d, 3σ • Surface pos: None • EDL Comm: None • Data volume: 15 Mb/sol avg • Contact freq: >1 pass per 4 sols
Netlanders (4) (CNES)	2007	• Latitude: -25 to +35 deg • Surface ops: 1 Martian yr • DTE: S- or X-band for EDL (tentative) • Proximity: UHF, 6.5 W RF transponder; add'l S- or X-band return link for radio sci • Power: Solar/battery	• Approach nav: 2.5 deg FPA error @ E-10d, 3σ • Surface pos: 2m (@end-of-mission) • EDL Comm: DTE (S- or X-band semaphores) • Data volume: Routine: 3 Mb/sol/lander; Events: 70 Mb/wk/lander • Contact freq: >1 pass per 4 sols • Radio sci: dual-freq return link to support NEIGE experiment
2nd Generation Lander (NASA)	2007	• Latitude: TBD • EDL control: aeromaneuvering and active hazard avoidance • Surface ops: 1 Mars yr • DTE: X-band, TBD EIRP • Proximity: UHF, 15 W RF transponder • Power source: TBD	• Approach nav: support landing accuracy of 6 km x 1.5 km, 3σ • Surface pos: TBD • EDL comm: DTE semaphores plus proximity link @ TBD kbps for characterizing aeromaneuvering and active hazard avoidance • Data volume: TBD • Contact freq: TBD
Competed Scout Missions (NASA)	2007, 2011 (tentative)	• TBD; most likely reliant on proximity link relay communications	• TBD
Mars Sample Return (MSR) Lander/Rover (NASA)	2011 or later	• Latitude: +- 15 deg (tentative) • EDL control: aeromaneuvering and active hazard avoidance • Surface Ops: 1 Mars yr • DTE: X-band, TBD EIRP • Proximity: UHF, 15 W RF transponder • Power: TBD	• Approach nav: support landing accuracy of 6 km x 1.5 km, 3σ • Surface pos: TBD • EDL comm: DTE semaphores plus proximity link @ TBD kbps • Data volume: TBD • Contact freq: TBD
MSR Mars Ascent Vehicle (NASA)	2011 or later	• Orbit: Targeting 500x500 km, 45 deg incl • On-orbit Life: <1 hr • DTE: None • Proximity: UHF; 1-way	• TBD comm during ascent to track and to characterize engineering system performance
MSR Sample Canister (NASA)	2011 or later	• Orbit: 500 x 500 km, 45 deg incl • On-orbit Life: TBD • DTE: None • Proximity: UHF; 1-way or 2-way	• Proximity comm for radio direction finding and/or line-of-sight doppler tracking to support orbit determination, on-orbit rendezvous

Table 1: Key Characteristics and Requirements of Proximity Link Users

spacecraft from the surface of another planet, is another crtiical event that will demand realtime tracking and telemetry. Finally, radio-based tracking techniques will be utilized to locate and rendezvous with the orbiting sample canister.

Table 1 summarizes the key characteristics and requirements of these various program assets which will utilize proximity link telecommunications and navigation services.

3 Telecommunications

Improvements in both the deep space link between Mars and Earth, as well as the use of proximity links between small surface or atmospheric spacecraft and Mars-orbiting relay spacecraft, will allow significant increases in data return over the coming decade while enabling new classes of small, low-mass mission concepts. Previous work [Edwards, et al., 2000] examined high-level telecommunications trades. Here we revisit some of these considerations in the context of the current exploration program plans.

3.1 Deep Space Links

First consider direct-to-Earth communications – the deep space link between a Mars spacecraft and Earth. Current science orbiters such as the Mars Global Surveyor are limited in their science data return by the constrained data rates achievable on these long distance links. For instance, MGS has only been able to return images for less than 1% of the planet's surface, at the 1.5-meter resolution of its onboard camera, due to deep space communications limits. The proposed 2005 Mars Reconnaissance Orbiter plans to carry an even higher-resolution imaging system, with a goal of achieving 30 cm surface resolution. This factor-of-five improvement in resolution translates into a factor of 25 increase in data for a given area on the Martian surface. Keeping up with this increased instrument performance will demand a more capable spacecraft communications system.

Figure 2 illustrates how increased spacecraft EIRP translates into increased deep space link performance. Shown are achievable data rates as a function of antenna diameter, for a range of transmitted RF power from a few watts up to a few hundred watts, assuming an X-band (8.4-GHz) link into a DSN 34m BWG antenna at maximum Earth-Mars distance. Also shown are specific points corresponding to the deep space radio system hardware for several recent or planned missions. (The quoted data rates are for illustration, based on simple scalings of power and antenna diameter, and are not meant to represent committed project capabilities.) MRO will provide more than an order-of-magnitude increase in data rate relative to MGS by increasing antenna diameter from 1.5m to 2.5m, and by increasing transmitted power from 25 W up to 100 W. These capabilities are well within the current state-of-the art, and allow a fixed aperture configuration that can be accommodated within current launch vehicle shroud dimensions. Further increases in EIRP and, in turn, Mars-to-Earth data rates can be achieved through a combination of:

- Additional increase in antenna diameter, with a transition to deployable apertures to accommodate launch vehicle constraints;
- Higher-power transmitters, ultimately limited by spacecraft power and thermal design considerations;
- Transition from 8.4 GHz (X-band) to 32 GHz (Ka-band) downlink communications frequency, with roughly a 6 dB performance advantage due to the increased

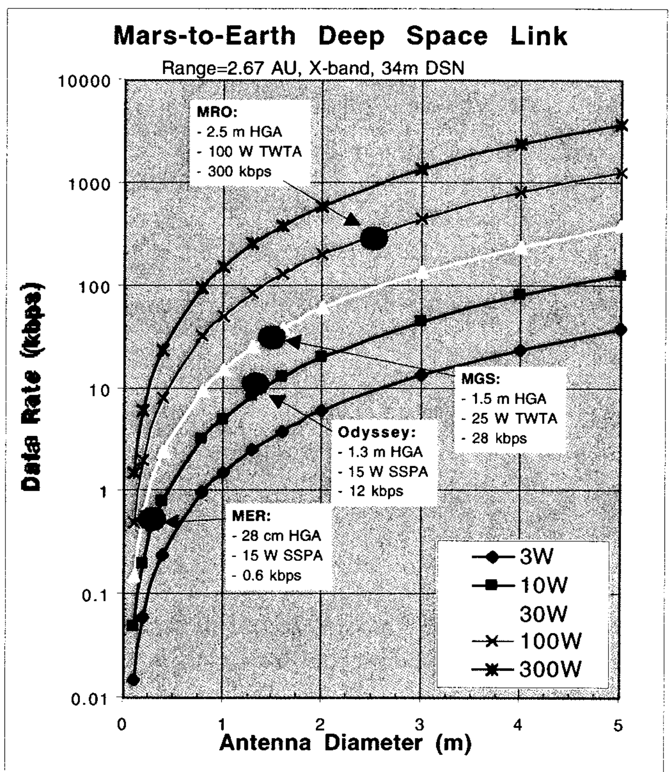

Figure 2: Deep space link performance as a function of spacecraft EIRP.

spacecraft antenna directivity at the shorter Ka-band wavelength;

- Increased ground aperture at Earth, either through use of the 70m antenna or arraying of multiple 34m antennas.

In addition to its potential for increasing spacecraft EIRP, the transition to Ka-band is also motivated by the need for increased spectral bandwidth. The 50-MHz X-band allocation will begin to get very crowded when we envision multiple spacecraft simultaneously at Mars, with multi-Mbps data rates and low-rate error correcting codes. The 500 MHz Ka-band allocation will be essential in order to support multiple high-rate users without interference.

Figure 2 also shows the anticipated DTE link performance for the 2003 Mars Exploration Rovers, based on their Mars Pathfinder-heritage X-band link which utilizes a 28-cm HGA and a 15W SSPA. The resulting link is less than 1 kbps at maximum Earth-Mars distance. This illustrates the fact that we will always have a significant gap between the magnitude of EIRP we can deliver to the surface relative to what we can place in orbit, due to the high cost, per unit of mass and power, of delivering payload to the Martian surface. This is the fundamental rationale for proximity link relay communications.

3.2 Proximity Links

Short-range proximity links offer the potential to move data from the surface of Mars to Mars orbit with a highly energy-efficient link, and then utilize the greater EIRP of the orbital relay spacecraft for the long-distance link back to Earth. One way to characterize proximity links is in terms of their operational antenna pointing considerations; i.e., whether either end of the link requires dedicated antenna pointing, or instead the antennas utilize "omnidirectional" patterns.

The simplest mode of operation is where both the surface user and the orbiter utilize omnidirectional (or, more accurately, fixed-gain) antenna patterns. This is the mode envisioned for the relay link between MER and Odyssey, with MER transmitting through a vertically-oriented monopole antenna, and Odyssey receiving through a nadir-pointed helix. No active antenna pointing is required at either end of the link, greatly simplifying operations, especially for the surface element. For a link of this type, with fixed gain at either end of the link, link performance scales as the square of wavelength. The 401/437 MHz UHF band used for current and near-term Mars proximity communications, with roughly a 75-cm wavelength, represents a compromise between this increased performance and the fact that radio component masses and volumes also increase with wavelength.

Rover Transmit Parameters		Ref. 1Watt Omni to Omni
1) Transmitter Power,	dBm	30.0
2) Transmitter Circuit Losses	dB	-1.5
3) Antenna Gain	dBi	0.0
4) EIRP	dBm	28.5
5) Modulation Index	deg	60.0
LINK PARAMETERS		
6) Elevation Angle, deg		
7) S/C Off-Boresight Angle, deg		
10) Distance	km	1000.0
11) Link Frequency	MHz	401.5
12) Atmospheric Attenuation	dB	0
13) Space Losses	dB	-144.5
S/C Receive Parameters		0 dBi Omni
14) Sky temperature	K	190.0
20) Antenna Gain Toward User	dBi	0.0
22) Receiver Feeder Losses	dB	-1.5
22a) Notch Filter	dB	
22b) Diplexer	dB	
22c) Connectors, Cables, Switches	dB	
23) Receiver Noise Figure	dB	1.5
24) System Noise Temperature	K	338.8
25) Noise Spectral Density	dBm/Hz	-173.3
26) Loop Bandwidth	Hz	100.0
Total Power Summary		
27) Received Power	dBm	-117.5
28) Received Pt/No	dB Hz	55.8
29) Carrier Power/Total Power	dB	-6.0
30) Received Carrier Power	dBm	-123.5
31) Carrier SNR in 2Blo	dB	29.8
Data Channel Performance		
28) Symbol Rate	sps	54,000
29) Data Bit Rate	bps	27,000
30) Data Power/Total Power	dB	-1.2
31) Data Power to Receiver	dBm	-118.8
32) Eb/No toReceiver	dB	10.2
33)Demod and Receiver losses	dB	-2.0
34) Eb/No Output	dB	8.2
35)Thrshld Eb/No BER<10E-6	dB	5.2
36) Performance Margin	dB	3.0

Table 2: Reference proximity link budget, for an omni-to-omni link with 1W RF power and 1000 km slant range.

Increased link performance can be achieved by applying a directive link on the orbiter. Now a simple nadir-pointed strategy is no longer possible for the orbiter, but the lander is still relieved of the burden of pointing. In this case the key issue is the aperture size of the orbiter antenna. For this case of a fixed-aperture size directive antenna at one end of the link, and a fixed gain antenna at the other end, link performance is to first order frequency-independent. However, for the orbiter antenna, the pointing accuracy requirements will increase with increasing frequency.

Finally, the highest proximity link performance can be achieved through the use of directional antennas at both ends of the link. This requires a capable lander that can point to an orbiter overhead, a capability that is not envisioned for small scout-class missions but is typical of larger landers that also utilize a directional DTE link. Here, link performance scales with the square of frequency, and hence higher frequencies are desired.

To provide a simple reference point for proximity links, Table 2 presents a normalized UHF (401 MHz) link budget for a 1 W transmitting element, 0 dBi antenna gain at both ends of the link, and a slant range of 1000 km. (This slant range corresponds approximately to the range between a surface user and a 400-km science orbiter viewed at an elevation of 15 deg.) With these assumptions, a data rate of 27 kbps can be achieved. We will use this as a reference from which we can scale for other parameters of transmitted power, antenna gain, or slant range.

A key parameter for any relay satellite is its orbit. MGS, Odyssey, and MRO will provide relay services from a low-altitude, near-polar, sun-synchronous orbit. The low slant range for this orbit allows for high instantaneous data rates, but overall data return is limited by the very short and infrequent passes. Figures 3 shows contact time (measured in hours of contact per sol) and normalized data return (measured in Mbits per sol per Watt of surface user EIRP) for a 400 km science orbiter, with a 93 deg inclination. For the low-latitude regions where most near-term lander missions will be targeted, only about 15-20 min of link contact is available per sol, with a data return of only 20 Mb/sol/W.

For these science orbiters, orbit selection is dictated by the remote sensing requirements of low altitude for high resolution, polar orbit for global coverage, and sun-synchronicity for fixed lighting conditions. The 2007 Marconi telesat, on the other hand, is the first dedicated Mars relay orbiter, and as such its orbit can be optimized for its telecommunications function. With this in mind, studies of a number of alternative orbits have been carried out. One attractive candidate is a mid-altitude orbit, with an altitude of 4450 km and an inclination of 130 deg. This combination of altitude and inclination establishes a sun-synchronous condition that maintains contact times at fixed locat times. The much higher altitude, relative to the 400

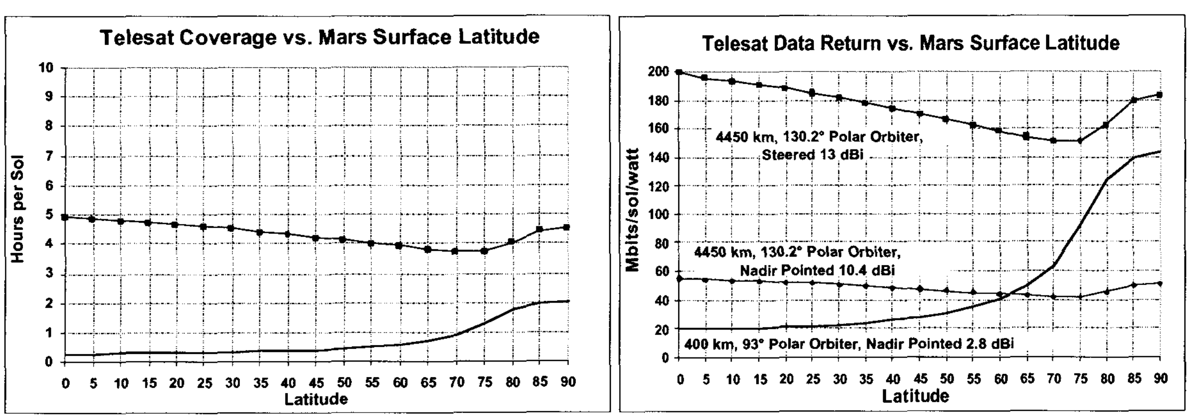

Figure 3: Coverage and data return for 400 km and 4450 km altitude telesat options

km science orbit, results in much greater contact time, and the inclination provides nearly flat coverage statistics as a function of latitude. On the other hand, the greater altitude reduces instantaneous data rate.

Figure 3 includes contact time statistics for this 4450 km altitude orbit. Contact time is increased to roughly 4-5 hrs/sol globally, representing an enormous increase relative to low-altitude science orbits. We have also examined data return for two different orbiter antenna assumptions. The first case maintains a simple nadir-pointed orbiter antenna. Relative to the low-altitude science orbiter, however, at this higher altitude the on-boresight antenna gain can be increased to 10.4 dBi while still maintaining a 3 dB beamwidth that covers the visible portion of the planet. This increased gain partially, but not completely, compensates for the increased slant range. Nonetheless, when combined with the longer pass times, this leads to increased data return for low-latitude users, relative to low-altitude science orbiters, with a data return of roughly 50 Mb/sol/W from any Mars latitude.

A second case has also been considered in which the orbiter carries a more directive 13 dBi UHF antenna, which is actively pointed at a surface user. The pointing accuracy requirements are minimal, as the antenna 3 dB beamwidth is about 50 deg. Due to the long wavelength at 400 MHz, however, this represents a fairly large antenna. The resulting increase in link performance, however, makes this option very attractive, with data return reaching nearly 200 Mb/sol/W. With a 10 W transmitter and omni antenna on the surface, such an orbiter could relay more than 1 Gb/sol from anywhere on Mars.

It is important to note that the increased data return for the 4450 km altitude orbiter is contingent on the lander's ability to fully utilize the increased pass time, since the instantaneous data rate is actually lower than for the lower-altitude science orbit. For large landers, this is viable, particularly since the lander would utilize a simple omnidirectional antenna. On the other hand, small scout-class misions may not have sufficient energy to allow many hours of transmission. For these missions for which minimizing energy-per-bit is the driving metric, and for which transmission time may be highly constrained, a low altitude science orbit with highest possible instantaneous data rate may be the best solution.

3.3 Critical Event Communications

After the loss of the Mars Polar Lander, at which time there was no active communications link, the program has established a policy of striving to ensure communications during critical mission events. From a program perspective, the availability of communications of sufficient bandwidth to support diagnosis of a mission anomaly provides essential feed-forward engineering knowledge that can be incorporated into subsequent missions. Examples of critical events include Entry, Descent, and Landing (EDL), Mars Orbit Insertion (MOI), and Mars Ascent Vehicle (MAV) launch. Recent analysis has focused on the support of real-time EDL communications, required for the 2003 Mars Exploration Rovers and also for the 2007 Smart Lander mission.

A limited Direct-To-Earth communications link can be established during EDL. Due to attitude uncertainty, such a link is support by a low gain antenna. The resulting very low SNR link can only support a very limited effective data rate, based on a sempahore signaling scheme in which one of a large number of tones is transmitted and detected with a DSN 70m antenna. With roughly a 10-sec integration time required for reliable tone detection, a 256-tone configuration represents a data rate of less than 1 bps. This scheme provides a baseline capability for a low-complexity EDL implementation such as is being used for MER. The MER EDL consists of a small number of state transitions based on a simple ballistic entry, parachute deployment, radar-based ground acquisition, airbag inflation, and impact. For this simple EDL, the semaphore-based DTE scheme may be able to provide adequate information to support any potential fault reconstruction. However, even for this case, the difficulty in assuring adequate DTE link margin due to unmodeled attitude dynamics during EDL, and the ability to only send one semaphore in the final 10 s of descent, has led the project to investigate the possibility of a higher-rate UHF link to MGS during the lower portion of EDL.

The need for a high-rate EDL proximity link becomes even more acute in 2007, with the second generation smart lander employing a number of new technologies. Given that the 2007 lander mission is largely intended as a feed-forward demonstration of critical EDL technologies needed for sample return in 2011, it will be essential from a program perspective to acquire sufficient engineering telemetry during EDL to adequately characterize the performance of these new technologies. In particular, active aeromaneuvering during hypersonic entry will involve high-bandwidth inertial guidance algorithms, and active hazard detection and avoidance during terminal descent will involve high-rate sensors and algorithms to identify and fly to a safe landing site.

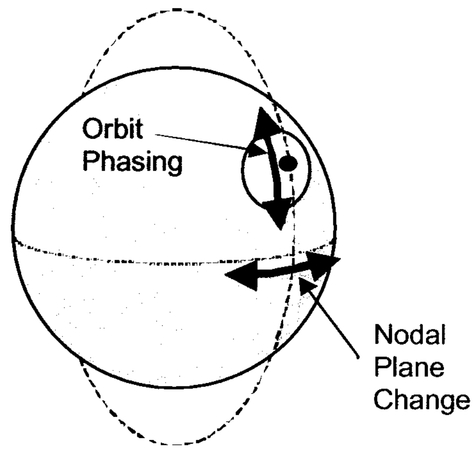

Figure 4: Orbit adjustments to support EDL relay communications link availability

We have performed an initial assessment of the ability of Mars orbiters to provide EDL coverage. The challenge here is that the orbital relay spacecraft must be positioned both spatially and temporally to be visible to the EDL vehicle. As depicted in Figure 4, it may be necessary to adjust both the plane of the orbit (i.e., the longitude of the ascending node) as well as the phase of the spacecraft in that orbit (i.e., the orbiter true anomaly) in order for the orbiter's communications footprint to cover the EDL event.

We have quantified the propulsive delta-V requirements for orbit adjustments that would potentially be required in order to satisfy these spatial and temporal conditions.

An in-plane phase change is accomplished by propulsively adjusting the mean motion rate n:

$$\frac{\Delta v}{v} = \frac{\Delta n}{3n}$$

where v is the orbital velocity. For a 400-km orbit altitude, this corresponds to about 3.9 deg/day for each m/s of delta V. A given angular phase change is effected by changing the mean motion rate in this way and then waiting until the required phase change accumulates. The top graph in Figure 5 shows the

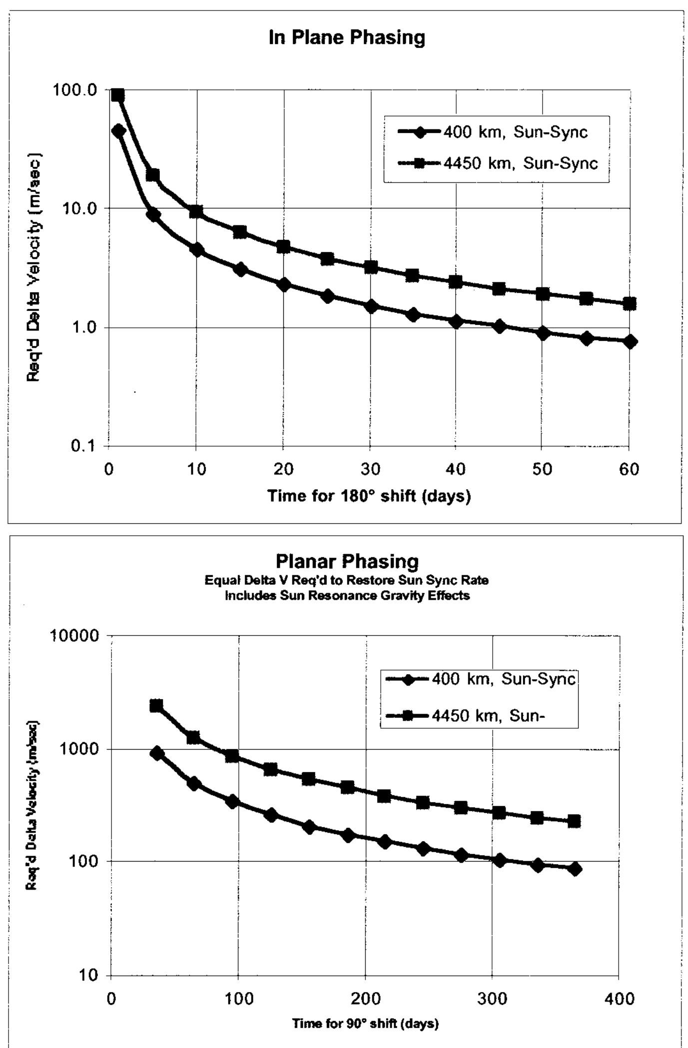

Figure 5: Propulsive Delta-V costs for orbit plane change and orbit phaseing maneuvers to support EDL

Orbit Altitude	Instantaneous Orbiter Comm Footprint (% of Planet)	Integrated Orbiter Comm Footprint Over Full Orbit (% of Planet)
400 km	2.5%	31.3%
4450 km	21.2%	81.7%

(Footprint calculated for 10 deg elevation mask)

Table 2: Comparison of EDL coverage statistics for 400 and 4250 km orbiters

required delta-V, as a function of how much time is allowed to the phase shift, to execute a worst-case 180-deg phase change. Clearly, the more time that is available to make the change, the less delta-v is required. For both the 400 and 4450 km orbits, worst-case phasing can be achieved on a time scale of one month for propulsive costs of 1-10 m/s, or lower if longer phasing time is available.

Planar phasing, or change of the orbital plane itself, however, is found to be significantly more costly. This plane change can be effected by propulsively making an inclination change and thereby inducing a nodal drift relative to the sun-synchronous condition. In this case, for circular orbits the delta-v cost is:

$$\frac{\Delta v}{v} = -\cot(i)\frac{\Delta\dot{\Omega}}{\dot{\Omega}}$$

where $\dot{\Omega}$ is the nodal rate, i is the inclination, and the Δv is normal to the orbit plane and executed at the equator. For the 400 km science orbiter, with ~93 deg inclination, the resulting nodal drift rate is only ~0.003 deg/day for each m/s of delta-v expended.

For inclinations greater than ~98 deg, it turns out that the nodal rate change can be more effectively induced by making a change in semi-major axis, rather than a change in inclination. In this case (again for the case of circular orbits), the resulting delta-v cost is

$$\frac{\Delta v}{v} = \frac{\Delta\dot{\Omega}}{7\dot{\Omega}}$$

Thus for the 4450 km orbiter, a nodal drift rate of only ~0.001 deg/day is achieved for each m/s of delta-v expended.

The lower graph in Figure 5 summarizes the propulsive costs of these plane changes for both the 400 km and 4450 km sun synchronous orbits. A worst case nodal change of 90 deg, achieved over 100 days, will require roughly 300 m/s for the 400 km orbit, and roughly 1000 m/s for the 4450 km orbit. Thus we see that the orbital plane change costs are much higher than the in-plane phasing. In addition, an equal delta-v cost would need to be expended to restore sun synchronicity. Finally, it should be pointed out that the nodal adjustment will vary the spacecraft-sun geometry and eclipse statistics, potentially driving spacecraft power and thermal issues.

The bottom line for EDL coverage is that in-plane phasing can be quickly executed at relatively low delta-v costs. This would allow the MGS spacecraft, for instance, to optimize its orbit phasing for both MER landers, which arrive roughly 1 month apart. On the other hand, it will not in practice be feasible to quickly execute orbit plane changes. A more reasonable strategy is to consider optimizing the nodal orientation of a relay orbiter once each 26-month Mars opportunity, based on the planned targeting of landers for that opportunity. The resulting long period for nodal drift reduces the required delta-v. Even this strategy has the potential to require significantly more delta-v for orbit phasing maneuvers than has been traditionally carried by previous science orbiters.

Finally, the much larger satellite footprint for a higher-altitude orbit has the potential to significantly increase the capability of the 4450 km orbit for supporting EDL events. Table 2 compares the the 400 km and 4250 km orbits in terms of two figures of merit: the orbiter footprint size as a fraction of the planet's surface area, and the portion of planet viewable over a full orbit, in a sun-fixed reference frame of latitude and solar time. The first metric assesses the instantaneous visibility; a larger footprint size will make it easier to satisfy EDL visibility, while a small footprint will require much more pricse orbital phasing. The second metric assesses how much of the lander targeting space can be covered with only an in-plane phasing maneuver. From the table we see that the 4450 km orbit provides nearly an order-of-magnitude larger footprint size, and can in fact view more than 80% of potential landing sites from a given orbit plane, with only an in-plane phasing adjustment.

A key issue for the program is whether the 2007 Marconi telesat will be able to provide EDL coverage to the 2007 smart lander. This will entail a coordinated mission design activity that examines whether the Marconi orbiter can arrive sufficiently in advance of the smart lander to be operationally ready to provide this service. (The fact that Marconi is currently baselining a chemical, non-aerobraking insertion will help to minimize time to on-orbit readiness.) Also, the local time of the Marconi orbit must be coordinated with the targeting strategy of the smart lander. While we have seen how the higher orbit altitude greatly increases the likelihood that EDL visibility can be achieved, it will be difficult to ensure visibility for the full range of smart lander targeting and mission timelines. As a result, the program is also examining the possibility of converting the lander cruise stage into a fly-by EDL relay platform. More detailed study is currently underway to further understand the potential for Mars orbital spacecraft to provide EDL coverage to the 2007 smart lander, incorporating actual geometries of candidate entry trajectories.

4 Electra Proximity Link Payload

JPL is currently in the process of defining a next-generation proximity link payload, called Electra, that would provide telecommunications relay and in situ navigation services for future Mars missions. With a first flight on MRO, this payload could be flown on all subsequent Mars orbiters, *de facto* interoperability and would enable the gradual implementation of a Mars orbital comm/nav infrastructure at low incremental cost. Key high-level goals for this implementation include:

- Flight reconfigurability to increase payload utility and accommodate new mission scenarios over long relay orbiter mission lifetimes
- Greater flexibility, including a wider range of supported data rates, swappable transmit/receive bands and multi-channel operation

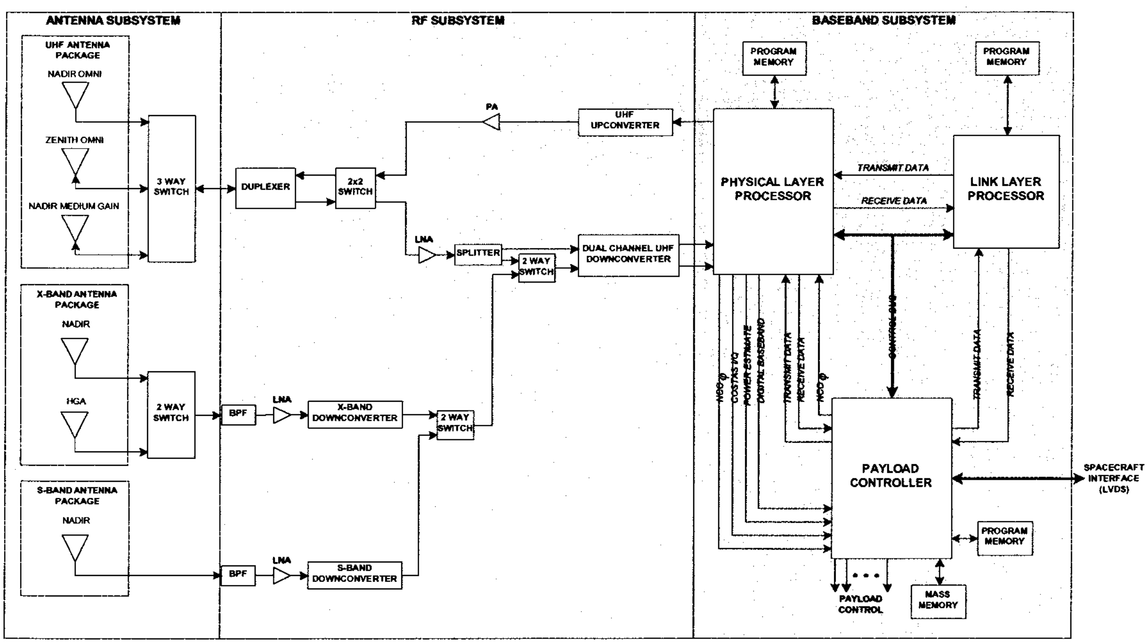

Figure 6: Functional block diagram of Electra proximity link comm/nav payload

- Full compliance with CCSDS Proximity-1 Link Protocol [CCSDS, 2000] and CCSDS File Delivery Protocol [CCSDS, 1999]
- Addition of X-band (8.4 GHz) receive capability, to support precision approach navigation and to allow very high-rate reception of data from a large lander equipped with a directional X-band DTE link.
- Improved navigation/timing performance
- Improved communications link performance through addition of Reed-Solomon coding, low-loss half-duplex operations mode, reduced receiver noise figure, increased power amplifier efficiency
- Modularity to allow scaling for low-mass lander/scout applications
- Portability to facilitate integration with variety of orbiters
- Self-contained relay functionality (including relay data management) for improved testability

Figure 6 illustrates a functional block diagram for the Electra payload, including options for addition of an S-band receive slice that could accommodate the radio science requirements of the Netlander NEIGE experiment [Barriot, et al., 2000]. Current plans call for completion of an engineering model of Electra in early 2003.

5 Summary

The coming decade of Mars exploration will demand improved telecommunications capabilities to meet the needs of a wide range of mission elements. Increased deep space link performance will enable return of large science data sets from high-resolution remote sensing orbiters such as the 2005 MRO mission. Proximity relay communications will be provided, based on a heterogenous constellation of science orbiters, equipped with a standardized comm/nav payload, along with the first dedicated planetary relay satellite, the 2007 ASI/NASA Marconi spacecraft. This orbital infrastructure must meet the diverse requirements of large, highly-capable second-generation landers/rovers as well as small, energy-constrained scout-class missions. Application of increases antenna gain on the orbiter will allow significant increases in data return while minimizing energy-per-bit requirements, especially for the higher-altitude orbits being considered for Marconi.

In addition to providing relay support during long-duration surface operations, the relay infrastructure will be called upon to provide realtime communications for critical mission events such as entry, descent, and landing. The spatial and temporal conditions required to ensure link availability for such events poses a difficult challenge. While in-plane orbit adjustments can be made with relatively little propulsive cost, changing the plane to rotate the orbit to a different local time requires very large propulsive maneuvers, with the costs scaling inversely with the time available to effect the change. Higher-altitude orbits will greatly increase the potential to satisfy these conditions due to much larger satellite footprint and ground track.

6 Acknowledgments

The research described in this report was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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